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Drying of the Panama Canal: Causes, Impacts and Mitigation Measures

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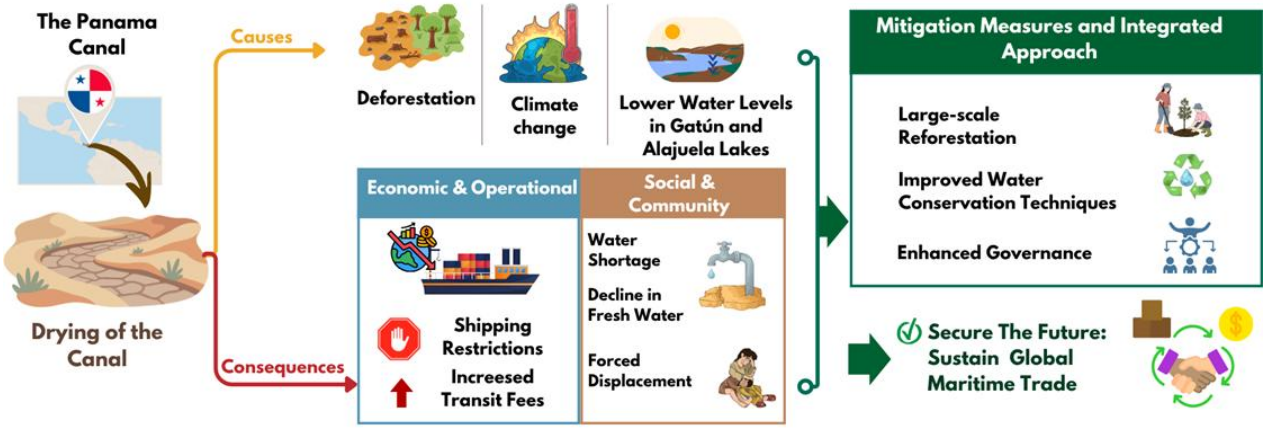
Graphical Abstract

The Panama Canal is threatened by freshwater decline due to deforestation and climate change. Falling levels in Gatún Lake and Alajuela Lake disrupt operations and impact communities. Integrated solutions such as reforestation and improved water management are essential for its sustainability.



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Abstract: The Panama Canal is facing severe operational challenges because of declining freshwater availability. Mass felling of trees in the watershed area of the Canal has drastically reduced the region's ability to retain water and attract rainfall. Rising global temperatures and irregular precipitation patterns caused by climate change have disrupted the Canal's freshwater supply significantly. This has resulted in lower water levels in Gatún and Alajuela Lakes, freshwater sources for the operations of the Canal. These declining water levels have led to shipping restrictions, increased transit fees, and economic strain on Panama's economy. Local communities are suffering from water shortage, forced displacement, and socio-economic instability because of conservation projects and alternative water management strategies. This study examines the underlying causes, consequences, and mitigation measures related to the drying of the Canal. Some interventions are identified: large-scale reforestation, improved water conservation techniques, and enhanced governance to mitigate this crisis. The Canal requires an integrated approach to secure its future in sustaining global maritime trade.

Keywords*: Panama Canal, Climate change, Gatún, Alajuela.*

Introduction

The Panama Canal, a crucial waterway that facilitates global trade, has been experiencing severe challenges caused by declining freshwater availability since late 2022 [1]. As a lock-based canal, it relies on movement of immense volumes of freshwater from Gatún and Alajuela Lakes to operate its locks and enable ship passage [2]. Yet, increase in global temperatures and changing precipitation patterns have led to prolonged droughts thereby decreasing the replenishment rate of these reservoirs. In addition, extensive deforestation in the Panama Canal watershed area has exacerbated water shortage by reducing the capacity of the land to retain and regulate rainfall. A combination of climate change, mass deforestation, and mismanaged water conservation efforts has reduced water levels drastically to threaten the Canal's functionality. Without sufficient forest cover, rainwater runs off quickly, leading to lower infiltration rate and increased evaporation, depleting water sources further.

The Canal's water crisis has widespread economic and social ramifications. Reduced water level has led to transit restrictions, limiting the number and size of ships that can pass, thereby increasing congestion and shipping costs. Since the Canal handles nearly 6% of global maritime trade, such disruption impacts international supply chains, raising transportation costs, and delaying shipments worldwide. Additionally, local communities that depend on the Canal for economic activities face significant water shortage as available freshwater is diverted to sustain Canal operations [3]. The resulting scarcity has intensified socio-economic challenges, particularly for rural and indigenous populations, many of whom rely on agriculture and fisheries that are directly affected by diminished water availability.

Despite extensive research on climate change and deforestation globally, there appears to be no published study of their combined impact on the Canal's sustainability. Although several conservation efforts such as reforestation programs and advanced water management technologies have been proposed, their implementation has been slow and has often met with political and economic resistance [4]. As a result, the Canal authorities have proposed construction of new reservoirs and implementing water saving measures, but the feasibility and long term efficacy of these solutions require greater assessment. This study thus aims to analyse the primary causes of the drying of the Panama Canal, its implications on the economy and populace of Panama, and the effectiveness of the proposed mitigation strategies to ensure a sustainable Panama Canal. The purpose is to provide insights into sustainable solutions that balance environmental conservation with economic needs; offering a holistic understanding of the crisis for Panama in general and the world as a whole. The study will thus bridge the gap between environment and economic needs by providing a comprehensive analysis of the Panama Canal's water crisis, integrating climate,

environmental, economic, and social perspectives. Additionally, the study will assess the long term economic risks associated with water shortages, the impact on vulnerable communities and the practicality of proposed mitigation strategies for Panama. The findings will contribute to informed policymaking and future research on sustainable water resource management in major trade corridors worldwide.

The paper begins with a literature review of the various studies undertaken by scholars, environmental experts, and policy institutions on the Panama Canal's hydrological challenges, with a focus on climate-induced droughts, impact of deforestation on watershed dynamics, and existing mitigation frameworks including reforestation programs, reservoir expansion, and advanced water conservation technologies. This will be followed by an analysis of the causes of drying of the Panama Canal, the multifaceted impacts of reduced water levels on trade and local communities, and discussion of proposed and implemented measures to address the present water crisis.

Literature Review

Drying of the Panama Canal has become an area of concern because of severe economic, social, and environmental repercussions. Accordingly, the Canal has been an area of study for researchers since the late 2000s after climate variability, unsustainable land use, and declining freshwater availability began visibly to affect its operational efficiency and long-term sustainability. Hence, it is important to examine key studies that have investigated the individual and collective causes associated with drying of the Canal. The earliest of these studies was by Estoque *et al.* [5] that highlighted the water concern for the Panama Canal. This study showed the way for many other studies that focused on climate change and deforestation as the primary cause for water shortage. But, significant gaps remained in understanding the long term consequences of water shortage and effectiveness of proposed mitigation measures. Hatvani *et al.* [6] found that the region has witnessed a 30% decline in annual rainfall over the past two decades caused by increasing global temperatures resulting in reduction of freshwater in the Gatún and Alajuela Lakes. Similarly, Aguilar and Naranjo [7] found that intensification of the El Niño phenomenon has prolonged droughts thereby exacerbating water scarcity and forcing the Canal authorities to impose transit restrictions. Without adaptation strategies, such climate related challenges will continue to disrupt Canal operations.

Since mass deforestation in the Panama Canal watershed has significantly reduced the region's ability to retain water, Fotos *et al.* [8] conducted a study demonstrating how extensive tree cutting has led to increased soil erosion, decreasing groundwater recharge and accelerating surface runoff.

They observed that this phenomenon prevents effective rainfall absorption, causing rapid depletion of freshwater reserves. Olson and Tornoe [9] found that deforestation in the Gatún Lake watershed has reduced water retention by 15%, leading to increased evaporation rates and lower lake levels, suggesting that reforestation efforts could play a vital role in reversing these trends.

Others have studied the economic impact of declining water levels in the Panama Canal. Kumar [10] estimated that a 20% decrease in Canal traffic because of water restrictions led to loss of billions of dollars annually in global trade. As the Canal becomes less reliable, shipping companies tend to seek alternative routes, reducing the economic competitiveness of the Panama Canal. Extending the argument, Aguilar and Naranjo [7] note that prolonged water shortage could permanently lower Panama's GDP by up to 5% through reduced revenue from Canal operations and associated economic activities.

The resulting water crisis has led to severe social and environmental challenges. Thomas [11] reported that prioritizing freshwater for Canal operations has worsened water shortages in nearby communities, leading to conflicts over resource allocation. Many rural and indigenous populations depend on the Canal's watershed for drinking water, irrigation, and fisheries. Olson and Tornoe [9] examined the environmental impact, revealing that reduced water levels have disrupted aquatic ecosystems, leading to habitat degradation and biodiversity loss in regions surrounding the Canal.

Accordingly, a number of mitigation strategies have been proposed. Suman *et al.* [12] explored the feasibility of constructing additional reservoirs to supplement the Canal's freshwater supply. Their study noted that such projects would require significant infrastructure investments and might displace local communities. Sasidhar [13] investigated the potential of water saving locks and advanced recycling systems, estimating that these innovations could reduce the Canal's freshwater consumption by up to 40%. Loewenberg [14] emphasized the importance of reforestation, suggesting that restoring tree cover in the watershed could significantly improve water retention and prevent further environmental degradation.

Despite extensive climate change research in Panama since 2007 [15] and hence research on the Panama Canal's water crisis, several gaps remain. Many studies focus on climate change and deforestation in isolation, but few examine their combined impact on the Canal's sustainability. Although some research highlights immediate economic losses, there is limited analysis of how prolonged water shortage could affect global trade and Panama's economy in the long term. Most studies have not explored the long term consequences of water shortages on local communities, including displacement, food insecurity and socio-economic instability. There has not been extensive study of the various mitigation strategies proposed, their real world feasibility, cost-

effectiveness and potential trade-offs. This study will focus on underlying causes, consequences, and mitigation strategies related to the drying of the Canal.

Working and Layout of the Panama Canal

The Panama Canal is a lock-based artificial waterway that connects the Atlantic Ocean (via the Caribbean Sea) to the Pacific Ocean, cutting across the Isthmus of Panama. Spanning approximately 80 kilometres, the Canal allows ships to avoid the much longer and more hazardous route around the southern tip of South America via Cape Horn. The core of the Canal's operation is its system of three lock complexes, Gatún Lock complex on the Atlantic side, and the other two, Pedro Miguel and Miraflores Lock complexes on the Pacific side as seen in Figure 1. These gigantic locks raise ships up to the elevation of the Gatún Lake (about 26 metres above sea level) and then lower them back down as they exit on the Atlantic side. The system relies entirely on freshwater, mainly from Gatún Lake and Alajuela Lake, to fill the lock chambers, enabling the transit of vessels through changes in elevation for either side movement, viz., the Atlantic to the Pacific (eastbound or north-to-south transit) and the Pacific-to-Atlantic (westbound or south-to-north) following different lock sequences and timing. The Atlantic-to-Pacific uses three-step Gatún Locks to lift ships 85 feet, followed by single-step Pedro Miguel (31 feet down) and two-step Miraflores (54 feet down). The Pacific-to-Atlantic movement follows the reverse order.

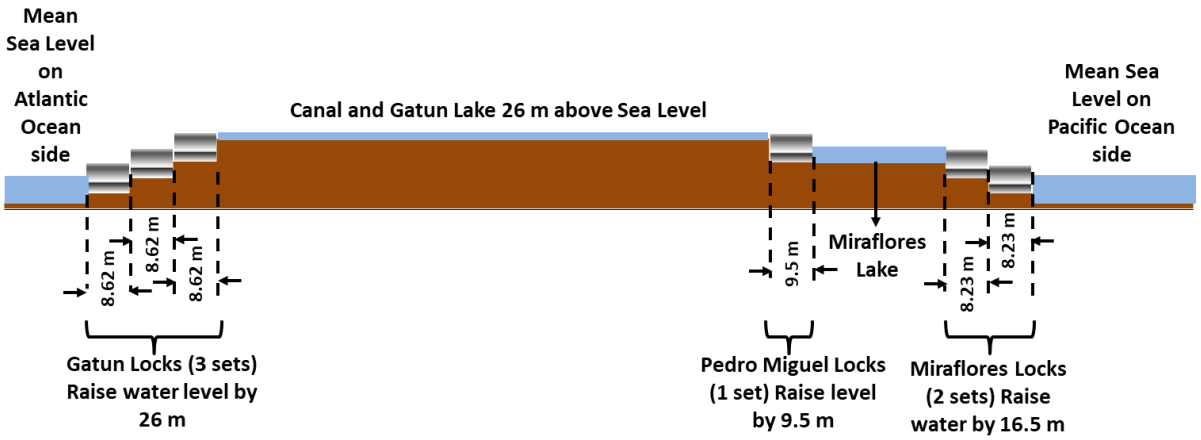
Mean Sea Level on Atlantic Ocean side
Canal and Gatun Lake 26 m above Sea Level
Mean Sea Level on Pacific Ocean side
8.62 m
8.62 m
8.62 m
9.5 m
Miraflores Lake
8.23 m
8.23 m
Gatun Locks (3 sets) Raise water level by 26 m
Pedro Miguel Locks (1 set) Raise level by 9.5 m
Miraflores Locks (2 sets) Raise water by 16.5 m

Figure 1. Layout of the Panama Canal (*Source*: Authors)

The flooding or draining of these Locks uses gravity-fed water from the reservoirs. To accommodate the growing size of ships, the capacity of the Canal was enhanced in 2016 by adding a third set of locks known as the Panama Canal Expansion (or "Neo-Panamax" Locks). This expansion allowed vessels of up to 366 metres in length to pass through. The freshwater-dependent design, though effective for nearly a century, makes the Canal vulnerable to shifts in regional

rainfall and water availability. A typical transit using Neo-Panamax Locks requires about 422 million litres of freshwater, of which nearly 40% is flushed into the sea after each passage whereas the older locks flush out 50% of the 200 million litres used [13]. For the Canal to function efficiently, Panama's wet season (May-December) must recharge reservoirs. But, water inflow has been reduced by 20-50% because of changes in El Niño and climate-driven events, increased evaporation and ship-induced salinity intrusion. Projections show that under high emissions the region is likely to experience droughts every 7-10 years by 2050 [16].

Causes of Drying of the Panama Canal

As discussed, the Panama Canal is a freshwater dependent, lock based canal. Each of the older lock chambers require about 98 million litres (26 million US gallons) (even after reusing 50% of existing water) of freshwater per fill. The new basin requires nearly 200 million litres (about 52.8 million gallons) (even after reusing 60% of existing water) to lift a vessel, drawn directly from Gatún Lake via gravity [13]. Owing to the surge in shipping and movement of larger vessels across the Canal, reducing water supply caused by drought, climate change, and deforestation, and an increasing population of Panama driven by a population boom, the available water in Gatún Lake is facing severe strain to meet drinking water requirements, Canal operations, and generating hydropower. The shortage is accentuated by leaky infrastructure that wastes close to 40-50% of municipal supply. Since the Canal is a critical maritime trade route, danger to its operations has a direct bearing on the world economy. Hence, it is important to look at the confluence of factors that have drastically reduced water availability, and which threaten both Canal operations and regional water security.

(a) ***Prolonged drought conditions.*** October 2023 was the driest month since the 1950s with recorded rainfall being 43% below the monthly average. The whole of 2023 was one of the two driest years in over seven decades and received an annual rainfall close to 20–30% below normal levels [17]. Although 2023 was one of the worst years, a cumulative water deficit severely impacted recovery of the main reservoirs. That points to a broader and worsening pattern of hydrological stress. Reduced precipitation in 2015-16, saw water level in Gatún Lake at 78.3 feet, nearly four feet below acceptable levels. In 2019, reduced water levels because of drought forced the Canal to impose shipping restrictions, reducing cargo loads, and increasing transit fees by up to 10% to manage congestion and costs. In 2023, even lower levels were recorded.

This reduced rainfall trend was compounded by rising regional temperature. Between 1980 and 2024, average temperatures in Panama have increased by approximately 1.1°C, accelerating rates of evaporation from reservoirs and reducing soil moisture retention [15]. A combination of insufficient rainfall and higher temperatures ensured that recovery of water bodies was slower even during the rainy season. These sustained drought conditions, coupled with watershed degradation caused by deforestation, significantly weakened the region's hydrological resilience.

(b) ***El Niño and Climate Change Amplification.*** One of the main causes of these critically low water levels was a significant deficit in rainfall during the 2023 rainy season (May–December), which sharply reduced the volume of water in Gatún Lake. Although water levels were above average in early 2023, a delayed rainy season with reduced precipitation caused by a shifting weather pattern resulted in the deficit. Such shifting patterns are strongly linked to the El Niño Southern Oscillation (ENSO) that typically brings drier conditions and shortened rainy seasons. Such a deficit was observed even in 2019. In 2023 it lasted longer till early 2024. Such climate drivers are slowly drying the Canal and making rainfall patterns in the region increasingly erratic. Climate models project that global warming is likely to make El Niño events more frequent and up to 15–20% stronger under high emission scenarios. This would eventually jeopardize the water stability and operational reliability of the Canal.

(c) ***Deforestation in the Canal Watershed.*** Widespread deforestation within the Panama Canal watershed has significantly contributed to declining water availability in the Canal's reservoirs. Forests in this region serve as natural water regulators by promoting infiltration, stabilizing soil, and maintaining the hydrological balance essential for feeding Lake Gatún and Lake Alajuela. This balance has been disrupted by decades of deforestation for agriculture, cattle grazing, urban expansion, and infrastructure projects. The Panama Canal watershed has lost nearly 20% of its forest cover between the 1970s and early 2000 [18]. This reduction has greatly diminished the landscape's capacity to retain and gradually release rainwater. In deforested areas, precipitation tends to run off rapidly rather than seeping into the ground, resulting in increased surface runoff, erosion, and evaporation [19] while increasing sedimentation in the Gatún and Alajuela Lakes, thereby reducing their effective storage volume and lifespan [20]. Thus, groundwater recharge and replenishment of critical freshwater reservoirs has reduced. Even during periods of normal or above-average rainfall, much of the water bypasses the Canal's storage system, reducing its capacity to sustain Lock operations [2].

Impact of a drying Panama Canal

A drying Panama Canal has profound implications at both the local and global level as it will disrupt maritime logistics and trade. A singular event of 2023 reduced daily vessel passages from 38 to 24 and resulted in delays, rerouting, and increased shipping costs. With climate change events more likely in a 'high emission scenario', the probability of the Canal drying increases multifold. Economists estimate that such disruptions could raise global shipping costs by up to 20% on certain routes and reduce Panama's GDP by 0.1–0.3% through lost revenue and congestion surcharges [21]. Local communities depending on the Canal for employment and economic stability face uncertainty as operations become less reliable. Environmental concerns also arise, as dwindling freshwater resources and ecosystem imbalances threaten biodiversity in surrounding regions. Without effective intervention, the drying of the Canal would have significant consequences, ranging from economic losses to environmental degradation and social instability. Let us examine these impacts at the local and global level in greater detail.

Local Impact

Declining freshwater in the watershed of the Panama Canal severely affects local communities by disrupting agriculture, access to drinking water, and community stability. Over 2 million people (half of Panama's population) rely on Gatún Lake for drinking water. A shortage of drinking water heightens health risks and forces rationing of this precious commodity both in urban and rural areas. It would increase forced migration resulting in economic isolation and reduced economic gains from tourism tied to the Canal.

(a) ***Water Shortages for Local Communities***. The Panama Canal requires approximately 200 million litres of freshwater for a single full ship transit. This requirement is met mainly by Gatún Lake and Alajuela Lake which together supply over 95% of the Canal's operational water needs [22]. With an average of 35–40 transits per day over 7 billion litres of freshwater is used daily which is equivalent to the daily water consumption of the entire population of Panama. During drought years, this demand competes directly with local and agricultural water needs, creating an unsustainable pressure on limited reservoirs and exposing the Canal's vulnerability to rainfall deficits [23]. When water levels drop, authorities prioritize the Canal's functionality over local needs as the Canal generates over $2.5–4 billion annually in tolls which is nearly 6–8% of their GDP. Low water levels in 2023–24 resulted in revenue losses of approximately $600–800 million, dwarfing local agricultural impacts and prompting global transit cuts [24].

(b) ***Economic Decline and Job Loss***. Panama's economy greatly depends on activities related to the Canal that include shipping, logistics and trade services. The revenue generated is through port operations, bunkering, transportation, toll revenues, and supporting jobs in sectors of piloting, port operations, ship maintenance, customs handling, freight forwarding, and warehousing. Such activities create opportunities for associated industries like banking, insurance, telecommunications, logistics providers, fuel suppliers, local shipping agents, tour operators, and catering services making the Canal the backbone of Panama's service-driven economy [25]. A reduction in daily vessel transit leads to decreased revenue and job losses in sectors tied to these maritime activities causing economic downturns in these sectors and those of port agency fees, eco-tours, and crew provisioning. Reduced water availability has resulted in fewer port calls, decreased cargo throughput, and less demand for ancillary services, particularly in key economic zones like Panama City and Colón. According to the Panama Chamber of Commerce, several small logistics firms reported a 15–25% drop in revenue during the second half of 2023, and local vendors and subcontractors near port areas experienced declining ship traffic and service demand [26]. This cascading effect shows that the Canal is both a maritime corridor and a lifeline for Panama's urban service economy.

(c) ***Environmental Degradation***. The water crisis has significantly aggravated environmental degradation within the Panama Canal watershed, with clear and measurable consequences. Fluctuating water levels, caused by erratic rainfall, over-extraction, and soil's limited ability to retain water have disrupted the ecological rhythms of freshwater habitats. Fish spawning cycles, amphibian populations, and riparian vegetation are particularly vulnerable to sudden changes in water depth and flow velocity. Species such as *Atelopus zeteki* the Panamanian golden frog (actually a toad) and certain native fish like *Aequidens coeruleopunctatus* have seen marked habitat contraction [27]. The resulting biodiversity loss not only threatens ecosystem health but also weakens the watershed's natural resilience against further climatic extremes. These environmental stresses could undermine the Canal's long-term operability, as ecological degradation further limits water availability and storage [28].

(d) ***Displacement of Local Communities***. To address freshwater shortage, the Panama Canal Authority (ACP) has proposed large-scale infrastructure projects, such as new reservoirs in Río Indio and Bayano basins to ensure operational stability for the Canal. These projects would have a high social cost as they would displace over 4,500 rural and indigenous residents including members of Ngäbe-Buglé and Emberá communities [29]. Since these communities depend on traditional farming, artisanal fishing, and culturally rooted land practices, relocating them is not just an economic disruption but a deep cultural loss. The proposed reservoirs would submerge

thousands of hectares of forest and farmland, threatening both biodiversity and livelihoods. Inadequate consultation and limited compensation have already provoked local resistance and protests. Displaced families often struggle to adapt to urban environments, leading to rising informal employment, housing insecurity, and social exclusion. This all deepens urban poverty and inequality, highlighting the complex trade-offs between environmental engineering and social justice in Panama's efforts to secure water for the Canal [30].

(e) ***Impact on Agriculture and Food Security***. With freshwater resources being diverted to sustain Canal operations, agricultural productivity in the region has been severely affected. Many farmers depend on consistent water supply for irrigation but declining water availability has resulted in lower crop yields, increased food prices, and financial instability for local agricultural workers [16]. The reduced harvests not only impact local food security but also affect Panama's ability to meet domestic demand and increasing dependence on imported goods. This shift places additional economic strain on lower income populations who already struggle with rising costs of essential goods.

Global Impacts

Disruption in movement across the Panama Canal caused by droughts has reshaped global supply chains by spiking shipping costs by 15-40% on key Asia-US routes and delaying commodities like LNG, grains, and containers [31]. Such changes have forced nearly 40% of the transits to be rerouted around South America. As a result, supply chains have been disturbed and have created inventory shortages in retail and automotive sectors. The drought of 2023 alone impacted approximately 5-7% of world trade connecting 170 countries [32].

(a) ***Disruptions to Global Trade and Supply chains***. The Panama Canal facilitates nearly 6% of global maritime trade between the Atlantic and the Pacific Ocean [32]. The operational capacity of the Canal will be significantly reduced if current weather trends continue. Since modern vessels are larger, they require more freshwater for each crossing. Because of reduced water levels during droughts in 2023 the Panama Canal Authority was forced to reduce daily ship transits to 24 from the earlier 36-38 forcing many shipping companies to seek alternative mechanisms such as impose cargo limits, reroute vessels, or increase freight charges. This resulted in widespread disruptions to global supply chains and brought about price volatility, delivery delays, and logistical bottlenecks across major markets [33].

(b) ***Rising shipping cost and Alternative routes***. Consequent to drought in 2023, the Panama Canal forced transit caps. Although it was anticipated that transits would return to full capacity by September 2025, recovery has been uncertain. In the first quarter of 2025, only 13 LNG (liquefied natural gas) vessels used the Canal and transits of dry bulk carriers dropped by 35% to 129. By the end of 2025, although the number of transits exceeded those in the previous drought period, driven by risks in using the Suez Canal, they were still lower than their averages [34]. So far, container vessels have maintained normal usage levels; but the decline in energy and bulk commodity transport shows the growing fragility of global supply chains amid climate driven disruptions. With transit restrictions in place, shipping companies are forced to use alternative routes such as the Suez Canal or around the southern tip of South America (Cape Horn). These options increase cost towards fuel and crew, transit times, and carbon emissions as was seen even for ships moving from Europe to Asia after the Houthi attacks in the Red Sea [35]. The rise in operational expenses is subsequently passed on to the consumers resulting in global inflationary pressures. This will be seen clearly when the March 2026 Israel and U.S. attacks on Iran are fully assessed in economic terms. Sectors that rely on just-in-time logistics, such as electronics and automotive industries, are especially vulnerable, and smaller businesses face mounting challenges in inventory management and meeting customer demand. Such shipping uncertainties have led to stockpiling, straining warehousing and logistics capacity, and increasing insurance premiums for extended voyages. Without a sustainable and climate resilient water management strategy, continued restrictions on Panama Canal transits may permanently alter trade routes and accelerate a shift toward more regionalized supply chains.

(c) ***Geopolitical and Economic Consequences***. Drying of the Panama Canal has broader geopolitical implications, as nations dependent on this trade route seek alternative solutions. Countries with major exports moving through the Canal, such as China and the US may shift trade agreements, invest in infrastructure projects, or explore new logistical hubs. Additionally, competition among global trade routes, such as the Arctic shipping lanes, which are becoming more navigable through increased global heating, could reshape international shipping patterns in the coming decades [36]. The disruption also strengthens the strategic importance of other major canals and ports, such as the Suez Canal and encourages developing rail networks connecting Asia and Europe such as the Belt and Road Initiative (BRI), India Middle-East Europe Corridor (IMEC), Asia-Africa Growth Corridor (AAGC), and the International North-South Transport Corridor (INSTC). Industries reliant on just-in-time shipping may accelerate investments in regional manufacturing and supply chain diversification to mitigate future risks. Furthermore, alliances and trade partnerships may shift as countries seek reliable and cost effective alternatives for transporting goods. The economic strain on Panama itself could prompt increased foreign

investments or influence from major global powers with an aim of greater control over critical trade infrastructure.

(d) ***Strain on International Energy Markets***. The disruption of Panama Canal transit has significantly impacted global energy supply chains, particularly for LNG and petroleum exports. Many energy shipments rely on the Canal for efficient transportation between major producers and consumers, including the US, Asia, and Europe. As delays force tankers to take longer routes, fuel supply uncertainties contribute to increased volatility in global energy prices. Rising transportation costs are passed on to consumers and industries, leading to higher electricity and fuel prices worldwide. Additionally, energy dependent economies face heightened risks of supply shortages, prompting governments to reconsider energy security strategies and diversify sourcing options. Some countries have begun stockpiling fuel reserves to cushion against potential disruptions, further driving up demand and market speculation. In the long term, sustained challenges in future Canal transit could accelerate investments in alternative energy sources and infrastructure to reduce reliance on fossil fuel imports. The rising cost and use of alternative routes as discussed earlier will add further to the existing strain on international energy markets.

Discussions and Way Ahead

The Panama Canal was built in 1904 as a means to move the US naval fleet between the Pacific and the Atlantic Oceans in quick time. After the Second World War, while the US continued to control the Canal it was opened to commercial ships, mainly the US ships, as a shorter trade route to Asia. It was only in 1999 that the Canal came under the full administrative control of Panama. Since then, the 82 km Panama Canal has been instrumental in transporting 5-6% of global maritime commerce annually in a cost effective and time saving manner. The operation of the Canal requires approximately 200 million litres of freshwater for the transit of a single ship which is supplied mainly by Gatún Lake and Alajuela Lake. Along with this requirement, these two lakes supply fresh water to the population of Panama while being dependent on rains for fresh water replenishment. In the event of a drought, as experienced in 2023, the lakes will show a major fall in available water levels. As in 2023, this event will, again, force authorities to reduce the number of transits.

This water shortage has had an impact both at the local and the global level. For the local communities, drinking water shortage became a major issue as Canal operations were given priority over supply of water to the residents. With the Canal supporting nearly 6-8% of their GDP, reduced transits impacted the GDP of Panama and the spin-off jobs associated with these transits. Over the

years, environmental degradation caused by deforestation and climate change events have reduced precipitation levels in Panama resulting in drying up of the lakes that support the Canal's operation. This will compound the problem. Agriculture will be affected by the reduced capacity to retain and gradually release rainwater. Again, there will be rapid runoff, erosion and evaporation of rain water rather than seeping into the ground.

Although deforestation has continued since the 1950s, the impact was realized only in 2023 when a severe drought reduced the water level of the lakes to minimum permissible levels. Since such events are an alarm, it is important that Panama makes efforts to conserve and protect their natural environment to minimize any effects of a future drought. Studies indicate that climate change events are likely to increase under high emission scenarios or the business-as-usual scenario. The Panama Canal thus requires a combination of environmental restoration, technological innovation, and policy reforms. This requires immediate and long-term measures to ensure sustainability of the Canal and its surrounding ecosystems while maintaining the economic stability of the country. Without proactive intervention, the water crisis in Panama will continue and threaten local livelihood, regional economies, and global trade. An integration of scientific research, stakeholder collaboration, and adaptive management strategies is thus essential for developing effective solutions. Securing adequate funding for conservation projects and infrastructure improvements is essential to implement these measures successfully. Some possible mechanisms are recommended for consideration.

(a) ***Large Scale Reforestation and Watershed Protection.*** Reforestation in the Panama Canal watershed is considered the start point to restore the region's natural ability to retain water. Expanding protected forest areas, enforcing stricter deforestation laws and giving landowners incentives for sustainable land use practices can significantly improve water retention and reduce soil erosion [37]. For example, the tourism industry in Panama should be encouraged to focus on these realities. Afforestation programs need to plant native tree species to enhance biodiversity and stabilize the ecosystem. Additionally, educating local communities about sustainable agricultural and forestry practices can prevent further land degradation. Local communities who adopt environment-friendly conservation practices need to be provided with financial incentives. Research institutions and environmental organizations need to be encouraged to assist in developing reforestation models tailored to Panama's unique climate conditions. By restoring forests and preventing further deforestation, Panama can create a more resilient watershed that supports both the Canal and local communities.

(b) ***Improved Water Conservation and Management.*** Adoption of advanced water saving technologies can optimize freshwater used for operations of the Canal. Renewing infrastructure to

minimize water loss through leakage and evaporation is crucial. Smart monitoring systems can be introduced to track water levels and predict shortages, allowing authorities to implement proactive measures [38]. Using digital twin technology, virtual simulations of real world infrastructure, can help optimize water management strategies [39]. Such efforts can be accelerated with the participation of private players either in a public-private partnership model or through full ownership by the private players.

(c) ***Development of Alternative Water Sources.*** Investing in rainwater harvesting systems can supplement freshwater availability for the region. Additionally, innovative water extraction methods, such as atmospheric water generators, could provide sustainable long term solutions. This needs to be adequately supported by community based water conservation programs to help distribute resources more efficiently, so that there may be equitable access to all. There needs to be also the use of enhanced groundwater recharge techniques to undo the diminished capacity of the soil to retain and release water. The integration of multiple water sources will create a more sustainable and adaptive system for managing water availability in the region. Although some may even recommend desalination plants to meet the water requirement of the country, they are not recommended as desalination plants have their own ecological concerns [40].

(d) ***Increase holding basins for recycling water from Locks.*** To reduce fresh water consumption from the lakes requires a comprehensive design that would need building new basins and integrating existing gravity-fed basins with active pumping. For the Neo-Panamax Locks, nearly 60% of water is recycled by using three basins created adjacent to the Lock (see Fig. 2). To ensure more water can be recycled, the existing basin system will need to be modernized to five in place of the existing three. For the older two-lane Locks, although nearly 50% of the water is recycled between parallel lanes (see Fig. 2), to save the remaining 50% water which is discharged into the ocean, new basins will be required wherein the water can be pumped into and from the Locks to minimize the demand of freshwater from lakes. This development must be preceded by a feasibility study. The existing water transfers are done using gravity without using power, but these proposed basin transfers will require mechanical pumping systems. Although these electrical pumps will be energy-intensive, the revenue from a transit greatly exceeds the cost of operations. The operations of these pumps can be made sustainable if operated with electricity produced from renewable sources. Although the entire transit per ship may increase, this sustainable development will ensure that the Canal's operations will continue even if droughts are experienced by the region. Higher availability of fresh water in the lakes will ensure the well-being of Panama's population and reduce migration, providing more economic activities in Panama and hence greater economic prosperity for the country. With 100% recycling, implementing reverse osmosis or multi stage flash

desalination plants at the lock interface will need to be established to avoid salt water intrusion into the freshwater ecosystem of Gatún Lake.

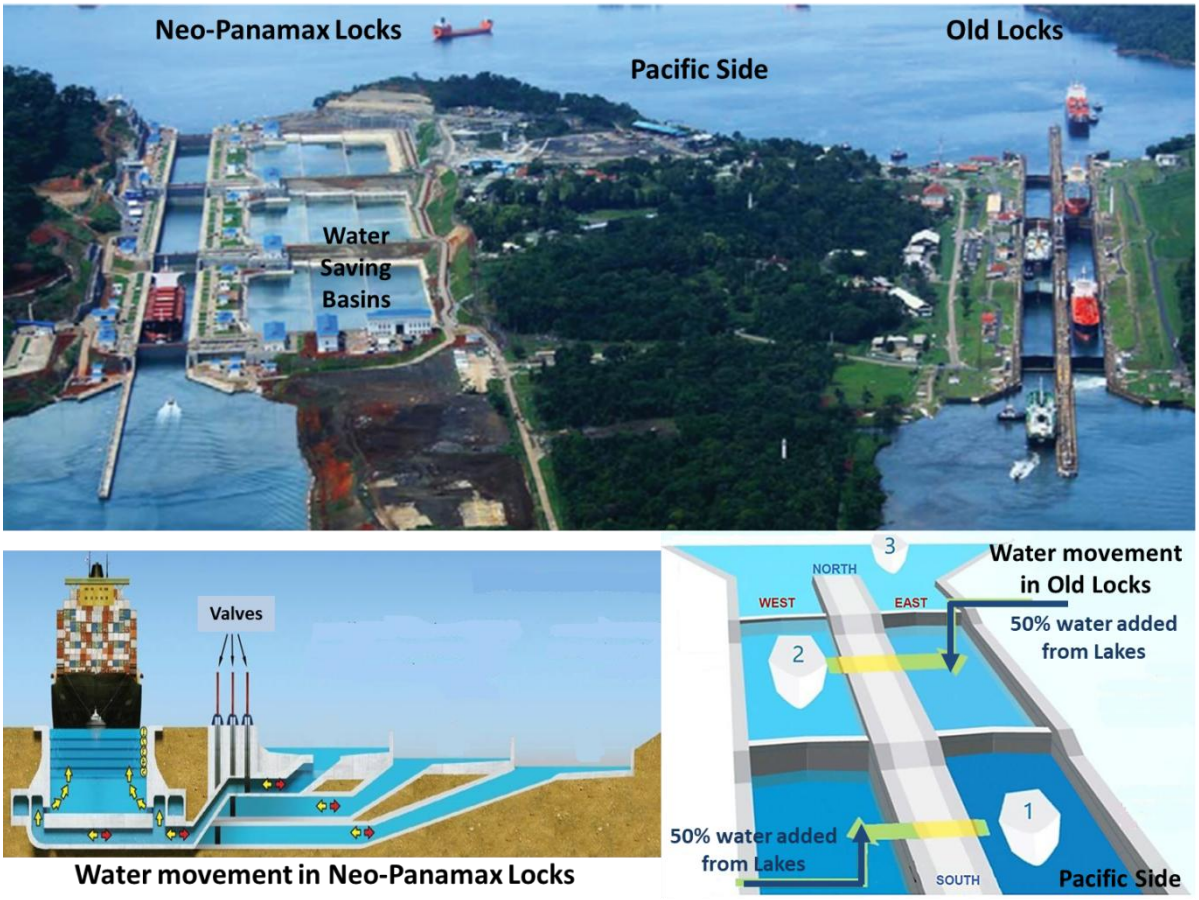

Figure 2. Water movement in Old and New Locks (*Source*: Authors, from various resources)

(e) ***Recycling Grey Water for reduced dependence on fresh water.*** Panama City lacks a centralized municipal grey water recycling programme for individual homes and hence implementing an onsite solution to address this issue will reduce the annual water consumption of the city. Mechanisms such as nature based solutions (NBS), mechanical filtration, biological treatment, and direct diversion are some common recycling methods that can be explored. Such treatment systems can be implemented by means of local service providers.

(f) ***Policy Reforms.*** Government policies are essential to prioritize sustainable water management through stricter environmental regulations and better resource allocation. This needs to be adequately supported with transparency in water governance, including public access to water usage data and decision making processes for greater accountability. Businesses could be persuaded to adopt water efficient practices through the incentives of tax benefits or subsidies. Participation in conservation efforts needs to be nation-wide. Strengthening the legal framework to end deforestation and illegal land exploitation is essential to avoid further degradation of the forest

cover. To adopt and introduce advanced technologies for conservation, international collaboration with trade partners and environmental organizations may be encouraged.

(g) ***Creating climate change resilience.*** It is considered essential to include in Panama's national policies the components of an integrated plan for climate change resilience through national adaptation, improvements in infrastructure, the use of nature based solutions, and an openness to data as they emerge, to maintain flexibility in policy for the sake of long term stability.

Conclusion

Drying of the Panama Canal is a multifaceted crisis driven by climate change, deforestation, and poor water management. The consequences extend beyond Panama, affecting global trade and regional livelihoods. Immediate and long term strategies, including reforestation, improved governance and sustainable infrastructure, are considered imperative. Strengthening international cooperation and fostering innovation in water conservation technologies will be a key to mitigate the existing crisis. Additionally, proactive policy reforms and economic diversification will help reduce Panama's vulnerability to future water shortages. These challenges require a holistic response that integrates environmental, economic, and social considerations. Without decisive action, the Canal's long term viability and its role in global trade will remain at risk. The present research has endeavoured to discuss the causes, impacts, and mitigation measures. The recommendations offered here integrate solutions that balance environmental conservation with economic sustainability. It is essential to include government agencies, private enterprises and local communities in the attempt to maintain the Panama Canal in a functioning state.

Although the construction of the Rio-Indio reservoir of the Panama Canal Authority approved in February 2025 is a long-term water security strategy which will ensure a minimum of 36 daily transits even during severe dry seasons and could potentially add up to 15 additional ship transits per day once fully operational, it faces serious property appraisals and community resettlement plans [41]. Nevertheless, ensuring resilience depends on stopping deforestation and coping with climate change. By integrating measures discussed in the paper, Panama can mitigate the Canal's water crisis, ensuring long term economic stability and environmental sustainability. Otherwise, the economic and geopolitical significance of the Panama Canal may decline, leading to long term global trade disruptions. Strengthening Panama's resilience against climate change will serve as a model for other water stressed regions worldwide. Investing in long term sustainability will not only benefit Panama but also secure stable maritime trade for generations to come and hence must be undertaken on a near war-footing.

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